

GLOBAL PRECIPITATION MEASUREMENT (GPM) AND INTERNATIONAL SPACE STATION (ISS) COORDINATION FOR CUBESAT DEPLOYMENTS TO MINIMIZE COLLISION RISK

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ABSTRACT

The Global Precipitation Measurement Mission (GPM) is a joint U.S. and Japan mission to observe global precipitation, extending the Tropical Rainfall Measuring Mission (TRMM), which was launched by H-IIA from Tanegashima in Japan on February 28TH, 2014 directly into its 407km operational orbit. The International Space Station (ISS) is an international human research facility operated jointly by Russia and the USA from NASA's Johnson Space Center (JSC) in Houston Texas. Mission priorities lowered the operating altitude of ISS from 415km to 400km in early 2105, effectively placing both vehicles into the same orbital regime. The ISS has begun a program of deployments of cost effective CubeSats from the ISS that allow testing and validation of new technologies. With a major new asset flying at the same effective altitude as the ISS, CubeSat deployments became a serious threat to GPM and therefore a significant indirect threat to the ISS. This paper describes the specific problem of collision threat to GPM and risk to ISS CubeSat deployment and the process that was implemented to keep both missions safe from collision and maximize their project goals.

1 INTRODUCTION

Spacecraft operators employ conjunction assessment to assure the safety of the space environment as well as the spacecraft. These processes rely on JSpOC screening of catalogued objects. New objects, such as CubeSats, take multiple days to be included in the catalog. In addition to performing routine conjunction assessment while on orbit, missions are required to perform a launch Collision Avoidance (COLA) to assure that the initial trajectory of the rocket and spacecraft will not be in close proximity with another space vehicle or debris. However, the same level of safety is not used during deployment of low-cost CubeSats from the ISS or other space-borne vehicles.

In 2012, ISS began a campaign to deploy CubeSats from the ISS. These low-cost small satellites are used for earth science, space environment science and technology demonstration vehicles and are delivered to the ISS on cargo missions. Once on station, they are deployed from various deployment mechanisms. To date, 157 CubeSats have been successfully deployed from the ISS, 119 of which have been done while GPM was on orbit. None of which are subject to a COLA. CubeSat deployments at this low altitude poses little risk to the majority of the space-faring community, except for a handful of satellites operating at nearly the same altitude, one of which is GPM.

This paper details the problem and the implemented solution that the ISS Project and the GPM Project have developed and employed to ensure that deployments from the ISS are safe to GPM and therefore to the space environment at that altitude.

2 GPM OVERVIEW

GPM is a joint mission between the National Aeronautics and Space Administration (NASA) of the United States and the Japan Aerospace Exploration Agency (JAXA). GPM was launched via a Japanese H-IIA Expendable Launch Vehicle (ELV) from the Yoshinobu Launch Complex (YLC), Tanegashima Space Center (TnSC), Japan. The GPM Core Observatory operates in a mission orbit of approximately 407 km with a 65-degree inclination. Note that 407 km is an average altitude that actually ranges from 397 to 419 km due to the non-spherical nature of the Earth – the true orbit is 6776.14 (varying ± 4 km) from the Earth's center of gravity.

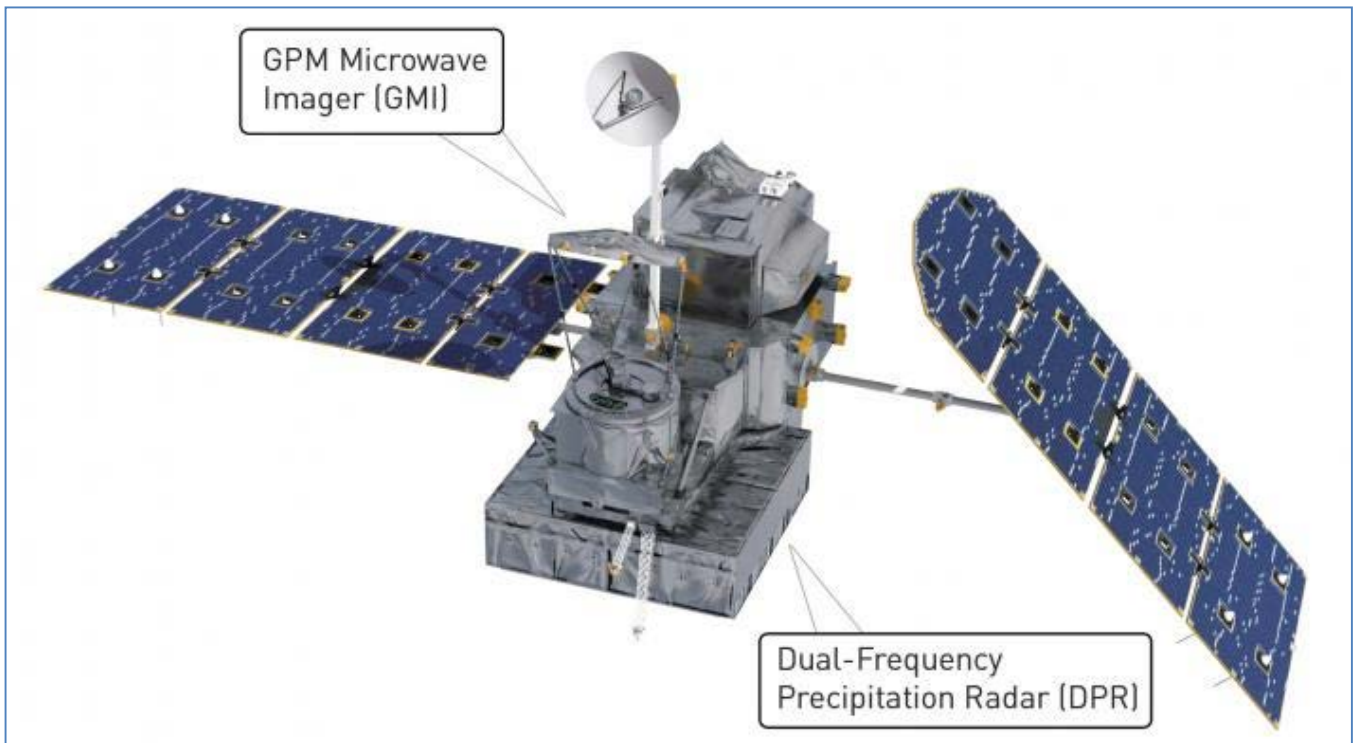


Figure 2-1: The GPM Core Spacecraft

GPM is a three-axis stabilized spacecraft (see Figure 2-1), nadir pointing for instrument observation of the Earth and its atmosphere, with the X-axis aligned with the velocity vector. The GPM observatory measures approximately 5.18 meters in length, 13.41 meters in width (with solar arrays deployed), and 3.66 meters in height, with a mass of approximately 3850 kg.

GPM utilizes the Conjunction Assessment and Risk Analysis (CARA) team at GSFC code 595 to provide notification of upcoming close approaches. The NASA Robotic collision risk assessment process is performed by the GSFC Robotic Systems Protection Program (Code 590.1). GPM MOC system shares predicted ephemeris data (including modeled maneuvers) with the CARA Team on a daily basis. CARA utilizes the Joint Space Operations Center (JSpOC) Goddard Orbital Safety Analysts (Goddard OSAs) to screen this data with all cataloged objects, including newly deployed CubeSats, to determine close approaches with the GPM spacecraft over the next seven (7) days.

Results of the screening process are delivered daily to the GPM project for situational awareness, and possible mitigation. Depending on the timeliness of the alert, the following action could be taken:

- 1) Emergency Debris Avoidance Maneuver (DAM)
- 2) Re-scheduling of a routine Drag Make-Up Maneuver (DMUM)
- 3) Request more tracking of debris object

GPM has the ability to perform both posi-grade (with the velocity vector) maneuvers and retro-grade (against the velocity vector) maneuvers. GPM could execute either maneuver as a response to a close approach situation.

3 ISS OVERVIEW

The International Space Station (ISS), depicted in Figure 3-1, is an international orbiting science facility that began construction in 1998, operated by the Flight Operations Directorate from the NASA Johnson Space Center (JSC) in Houston, Texas, and has been permanently manned since November 2000. Cooperating, in partnership, with National Aeronautics and Space Administration (NASA) are the Russian Space Agency, the Japan Aerospace Exploration Agency (JAXA), the Canadian Space Agency, and the participating member countries of the European Space Agency (ESA). The ISS uses capabilities of different space vehicles to launch utilization and resupply items, and crew on orbit. Space vehicles of various designs are used in support of these functions, which are generally called visiting vehicles (VVs). ISS also is used to deploy small satellites, commonly referred to as CubeSats and MicroSats, through several different deployment mechanisms.



Figure 3-1: The International Space Station

The ISS translation maneuvers (also known as reboosts) are driven by the VVs schedule and rendezvous/departure plans of those vehicles, the availability of propellant (driven by propellant resupply vehicles) and existing drag environment. ISS has operated at various altitudes during its mission life, from 335km to 420 km. ISS is currently operating at an altitude of approximately 400 ± 10 km. It is expected to remain in this altitude regime for the foreseeable future.

The ISS Trajectory Operations and Planning Group (TOPO) at Johnson Space Center (JSC) assess orbital debris threats to the ISS and its VVs and potential mitigations of upcoming close approaches. The ISS is screened by the JSpOC Human Space Flight (HSF) OSAs against the high accuracy catalog every eight (8) hours for the upcoming 72 hours. The VVs are also screened routinely during their rendezvous and departure free flight periods. Screening method/details vary by vehicle, but all come through the TOPO console. NASA/MCC-Houston (MCC-H) calculates Probability of Collision (P_c) upon notification and data from JSpOC.

ISS has the ability to perform both posi-grade (with the velocity vector) maneuvers and retro-grade (against the velocity vector) maneuvers with both the legacy DAM and Pre-determined DAM (PDAM). A PDAM is simply a DAM that is pre-loaded and resident on the ISS with a set burn duration that allows for minimum preparations. In the event of a late notification conjunction with a P_c that violates the ISS thresholds and a PDAM cannot be performed the crew will take shelter in the Soyuz spacecraft.

4 CLOSE APPROACH AGREEMENTS

Since the GPM and the ISS fly similar Semi-Major Axis (SMA) orbits, the following agreements have been established to maintain situational awareness of the other mission maneuver plans, and to maintain current contact information for potential contingency situations. VVs can be considered included with the ISS agreements below.

In addition to the following agreements, the CARA JSpOC Goddard Orbital Safety Analysts (OSAs) share the GPM predicted maneuver ephemeris with the HSF OSAs. This allows screening between ISS maneuvers and GPM maneuvers. This process is detailed as an SOP at the OSA level. Routine ISS screening of the GPM O/O ephemeris would catch any issues caused by near-term GPM DAMs and/or ISS DAMs. With this addition, it is expected that all close approaches between the missions will be caught by CARA and/or TOPO.

- | | |
|----------------|--|
| Agreement #1: | GPM agrees to share the GPM Advanced Maneuver Plan when produced, which includes planned propulsive maneuvers, such as DMUMs, with TOPO. |
| Agreement #2: | GPM agrees to share the GPM Maneuver Notifications, when produced, with TOPO. |
| Agreement #3: | TOPO agrees to share planned propulsive activities, such as reboosts or DAMs with the GPM Project as soon as is practicable. |
| Agreement #4: | TOPO agrees to share planned deployment activities, such as CubeSat releases or jettison candidates, with the GPM Project as soon as is practicable. |
| Agreement #5: | GPM agrees to notify TOPO of a predicted close approach with ISS within 24 hours of the initial notification. |
| Agreement #6: | TOPO agrees to notify the GPM Project of a predicted close approach with GPM within 24 hours of the initial notification. |
| Agreement #7: | GPM agrees to consult with TOPO when analyzing and preparing to mitigate a GPM/ISS close approach. |
| Agreement #8: | TOPO agrees to consult with the GPM Project when analyzing and preparing to mitigate a GPM/ISS close approach. |
| Agreement #9: | GPM agrees to share updates regarding a close approach with TOPO. |
| Agreement #10: | TOPO agrees to share updates regarding a close approach with the GPM Project |
| Agreement #11: | GPM agrees to notify TOPO of a waived DAM. |
| Agreement #12: | TOPO agrees to notify the GPM Project of a waived DAM. |
| Agreement #13: | GPM agrees to provide TOPO a DAM <i>Results Summary</i> . |
| Agreement #14: | TOPO agrees to provide the GPM Project a DAM <i>Results Summary</i> . |

5 CUBESATS AND JETTISONED OBJECTS DEPLOYMENT AGREEMENTS

ISS has begun a routine program of releasing CubeSats along with other jettisoned objects. GPM had conjunction concerns with the release of these objects since the objects are small and take a number of days to properly track and catalog.

ISS plans deployments/jettisons months in advance. These scheduled deploys are adjusted for operational considerations up to the final deploy/jettison date. ISS routinely conducts a “recontact analysis” to ensure that the deployed/jettisoned object does not have a close approach to the ISS. Acceptance of jettison candidates in general is governed by Partner Program Directive (PPD) 1011: Multilateral International Space Station (ISS) Jettison Policy. Following the deployment/jettison, ISS reports the deployment/jettison to JSpOC for tracking and cataloging. JSpOC tracking and cataloging of objects deployed/jettisoned from the ISS can take up to 6 days and is dependent on the number of payloads/objects deployed/jettisoned. Once the ISS-deployed/jettisoned object is catalogued, ISS and GPM can use the existing JSpOC and CARA process to predict and prepare for possible conjunctions and debris avoidance maneuver planning. Prior to cataloging, the risk to GPM posed by the deploy is undefined because the deployed/jettisoned object’s orbit is unknown.

On January 28TH, 2015, ISS entered the operational orbit of GPM following a planned drift down and deboost (Figure 5-1). Prior to this (drift down and de-boost ~Nov 2014), ISS had been flying roughly 10km above GPM. This scenario created a

conjunction risk to GPM, and ISS. Prior to this, GPM had relied on the radial separation between the missions to ensure adequate tracking and cataloging of the objects.

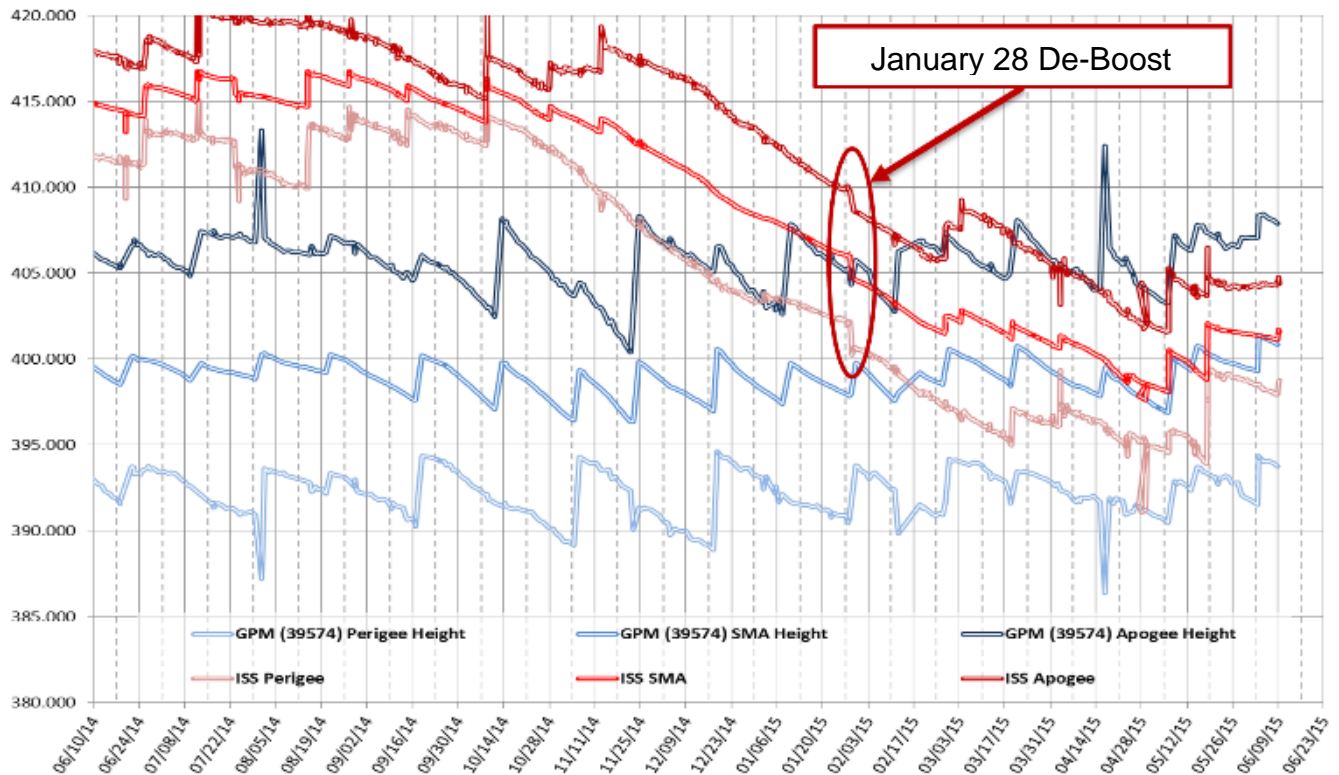


Figure 5-1: ISS & GPM Orbital Altitudes

Releasing payloads and other objects at roughly the same altitude of another high value NASA asset can potentially create a close approach that cannot be foreseen and therefore cannot be reacted to. A collision or debris generating event for GPM would cause a threat to ISS as a result. The problem is depicted in Figure 5-2. Quality tracking of a cubesat including covariance information is needed from JSpOC to treat it as a standard object in the catalog to determine the risk of a collision. Experience from ISS deploys indicates how long that takes is dependent on the number of objects deployed. The best practice used by ISS when performing risk analysis, allows for 4 days to obtain high quality tracking of a cubesat when 3 or fewer objects are deployed and 6 days if there are more objects. Therefore, during this period of time the trajectory is “unknown and unactionable”.

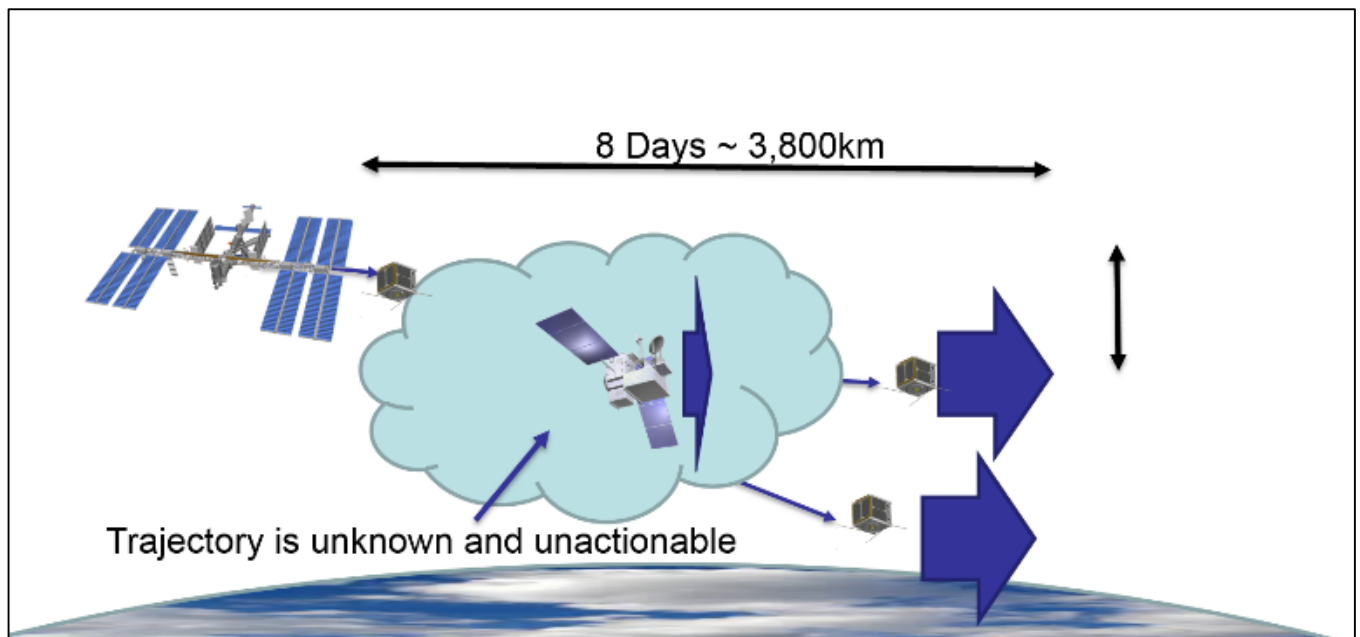


Figure 5-2: Deployment/Jettison Bad Day Scenario

Understanding this problem, the ISS and GPM Projects have constructed a process to mitigate the collision risk to GPM during this timeframe. It is assumed that once past this timeframe, GPM can and will react to a close approach with the deployed/jettisoned object the same as any other close approach. This process applies to objects released from ISS directly or deployments from Visiting Vehicles (VVs) to the ISS, such as deployers installed on Cygnus.

To allow use of the nominal collision avoidance process, a two day buffer is added to the amount of time required to catalog the objects. The process to mitigate the risk focuses on this 6 or 8 day timeframe. For a campaign of deploys, the time of concern begins with the first deploy and ends at 8 days after the final deploy.

A multi-step process has been developed to determine the risk posed by the deploy/jettison to GPM, while maintaining minimal effort for most other deploys/jettisons. Each additional step of analysis increases in fidelity in an attempt to determine if there is any risk to GPM posed by the deploy/jettison. If a step results there is no risk to GPM, then no further analysis is required. Otherwise, the analysis is refined and proceeds to the next step. To begin the process, the GPM and ISS teams share orbital data and jettison plans to ensure that both teams have situational awareness and provide the necessary inputs for analysis of the deploy/jettisons.

The first analysis attempts to rule out the possibility of a conjunction during this timeframe by showing that, for the worst cases, the deploy/jettison will not cross paths with GPM. This is done by comparing GPM's motion relative to ISS to the deploy/jettison's worst case motion relative to ISS. The area between the bounding worst cases for the deploy/jettison represent all the possible trajectories and is called the Deployment Zone (DZ). If any possible downtrack profile of the deploy/jettison does not intersect GPM's downtrack profile with respect to ISS, then, within the bounds of the analysis assumptions, there can be no conjunction during the time of concern. A description of the construction of the worst case deploy/jettison trajectories, the assumptions used and a further description of this one dimensional approach can be found in section 6: The Deployment Zone. If this analysis is satisfied, the planned deploy/jettison is safe with respect to GPM and no further analysis need be performed.

The second analysis adds another dimension by focusing on the radial separation at the common node between the deploy and GPM. The previous analysis did not account for the fact that the deploy and GPM will not be in the same orbital plane and therefore, the only risk occurs at the node between the two orbits. Once a common node is determined, GPM is stepped (either by propagation or via ephemeris file) to a location within its orbit where the downtrack separation or phase angle between GPM and the deploy is zero. Then, the radial difference between GPM and deploy is calculated. This analysis is similar to the collision avoidance analysis performed between launches and on orbit assets. For newly launched objects, this method is used to account for the large downtrack dispersions associated with launch vehicles; in the case of a deploy from ISS, this method allows for uncertainty in the deploy time, speed, atmosphere and ballistic characteristics which translates to downtrack uncertainty. If the radial separation of all the possible deploy trajectories is greater than acceptable distance from GPM for

safety plus the difference between ISS apogee and perigee over the entire time of concern, the deploy is safe with respect to GPM and no further analysis need be performed. The apogee/perigee difference must be taken in account if the deploy time is not assumed to be fixed. Through this method, a deploy can be proven safe, within the assumptions of the analysis, without fixing the time of the deploy.

The third analysis fixes the time of deploy and thereby allows consideration of the miss in 3 dimensions. For this analysis, the true miss at the common node between the deploy and GPM is recorded; GPM's position is not altered. A standoff ellipsoid about GPM takes into account a standoff for safety and uncertainty in GPM's predictions. If all the possible deploy trajectories result in common node misses outside GPM's ellipsoid, the deploy is safe with respect to GPM and no further analysis need be performed. This analysis is specific to deploy time and can distinguish which specific times are unsafe.

Both the second and third analysis attempt to prove that the object will not enter the Keep Out Volume (KOV) around GPM.

Deployments that cannot be proven safe by the methods presented above, will be elevated as a collision risk.

This decision process is depicted in Figure 5-3.

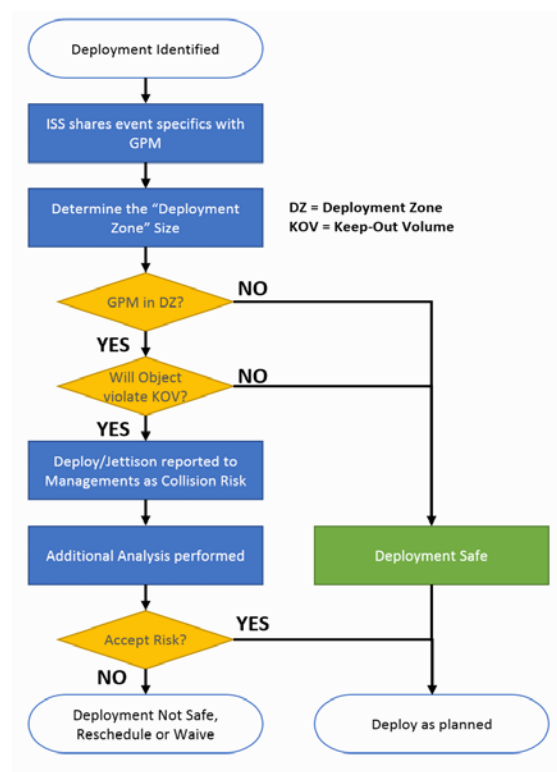


Figure 5-3: Deployment/Jettison Decision Flow

ISS has deployed several payloads from the five (5) different deployers on the ISS. Payloads and payload deployers arrive on ISS as pressurized cargo from a supply mission. They are transferred outside ISS for deploy via the Japanese Experiment Module Air Lock (JEM-AL) then moved to the deploy position by JEM or Space Station Remote Manipulator System (SSRMS). Deploys are commanded from the ground, and are deployed retrograde/Nadir to avoid long-term recontact with ISS. This deployment strategy results in a forward motion of the payload relative to the ISS. Deployers do not return any telemetry so live video and daylight are required to confirm a successful deploy. Each deployer is unique and presents differing separation velocities and capacity for CubeSats deployed at a time, resulting in the need for deployment zone tables from which a deployment zone can be derived.

5.1 JEM SMALL SATELLITE ORBITAL DEPLOYER (J-SSOD)

The JEM Small Satellite Orbital Deployer (J-SSOD) consists of two (2) 3 U deployers. The J-SSOD has a deploy capacity of 6U and two (2) deploy events can be completed in 1-2 days. Figure 5-4 shows the J-SSOD mechanism and Figure 5-5 shows the J-SSOD on orbit.



Figure 5-4: J-SSOD

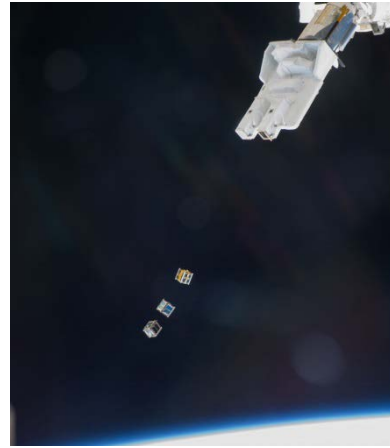


Figure 5-5: J-SSOD Deployment

5.2 JEM SMALL SATELLITE ORBITAL DEPLOYER M1 (J-SSOD M1)

The JEM Small Satellite Orbital Deployer (J-SSOD) M1 is designed to deploy a larger volume small satellite than the J-SSOD deployer. Figure 5-6 shows the deploy mechanism and Figure 5-7 shows the planned deployment position on orbit.

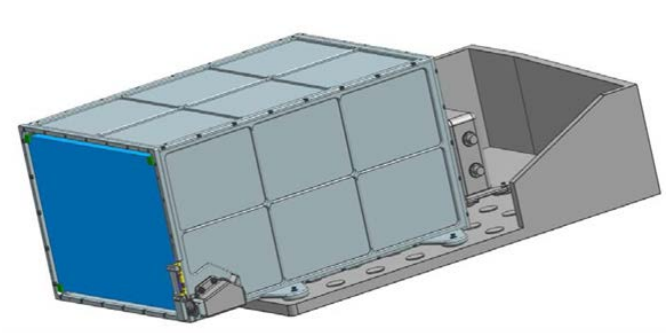


Figure 5-6: J-SSOD M1

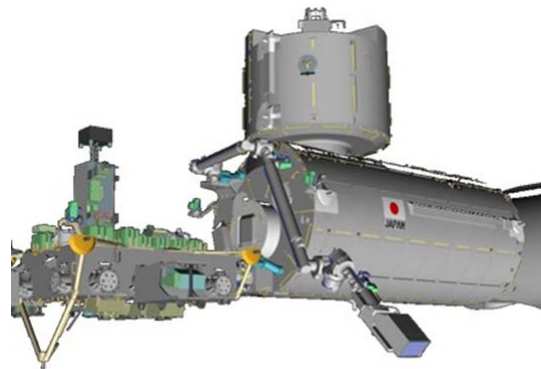


Figure 5-7: Planned J-SSOD M1 Deployment

5.3 NANORACKS CUBESAT DEPLOYER (NRCSD)

The NanoRacks CubeSat Deployer (NRCSD) consists of eight (8) 6 U deployers. The NRCSD has a deploy capacity of 48U and eight (8) deploy events can be completed in 2-3 days. Figure 5-8 shows the NRCSD mechanism and Figure 5-9 shows the NRCSD on orbit. Empty deployers return on Dragon for reuse.

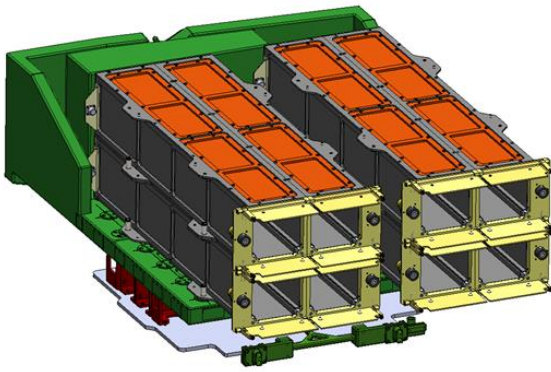


Figure 5-8: NRCSD



Figure 5-9: NRCSD Deployment

5.4 SPACE STATION INTEGRATED KINETIC LAUNCHER FOR ORBITAL PAYLOAD SYSTEMS (CYCLOPS)

The Space Station Integrated Kinetic Launcher for Orbital Payload Systems (Cyclops, originally named SSIKLOPS) was developed by JSC Engineering Directorate to deploy single large payloads up to 100 kg that maximize use of the JEM-AL volume. The Cyclops is moved to deploy position by the JEM-RMS/Small Fine Arm (SFA) or SSRMS/SPDM and is stored on ISS for reuse. Figure 5-10 shows the Cyclops deployed and ready to deploy SpinSat and Figure 5-11 shows the Cyclops awaiting to be moved to a deploy position.



Figure 5-10: CYCLOPS With Spin Sat

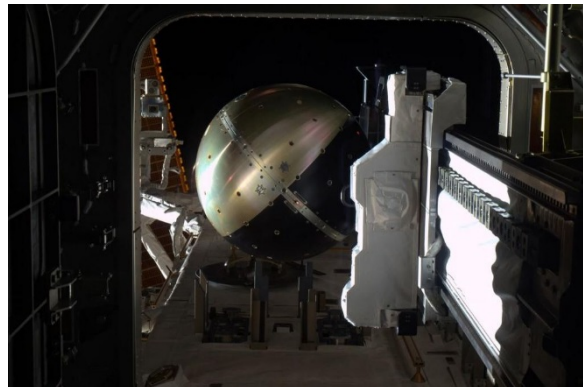


Figure 5-11: Cyclops/SpinSat awaiting Deploy

5.5 NANORACKS KABER

The NanoRacks Kaber Microsatellite Deployer System is an on-orbit small satellite deployment system that will be used to deploy satellites from the ISS. Its deploy capabilities are similar to Cyclops, but it is designed to deploy payloads with the Special Purpose Dexterous Manipulator (SPDM) utilizing the Japanese Experiment Module (JEM) airlock and slide table.

Payloads that are to be deployed by Kaber will be integrated with the deployer on-board the ISS by ISS crew members. The deployer/payload is then transferred out of the ISS via the JEM airlock. Once outside, Kaber will be retrieved by the Space Station Remote Manipulator System (SSRMS) / Special Purpose Dexterous Manipulator (SPDM) and moved to the appropriate deploy location. Once in the deploy location and orientation the payload is deployed. NanoRacks Kaber is shown in Figure 5-12.

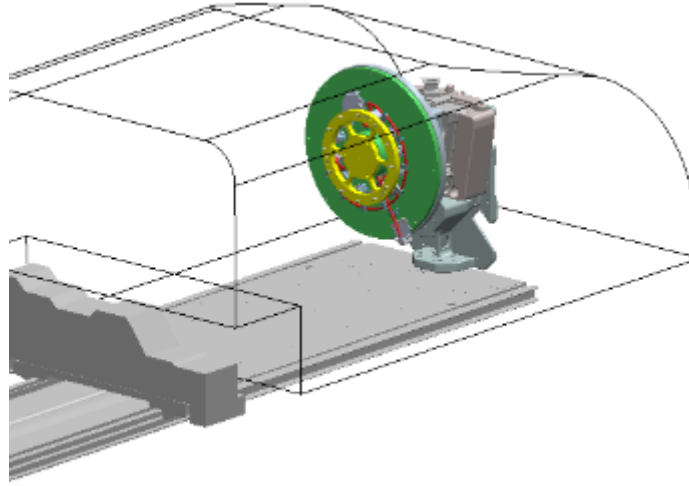


Figure 5-12: Kaber shown installed on the JEM airlock slide table with no payload attached

5.6 OTHER DEPLOYMENTS/JETTISONS

On a much smaller frequency, ISS has discarded other objects for disposal by jettison, mostly done by astronauts during an extra vehicular activity (EVA). These disposals/jettisons are to be handled similarly as other planned deployments.

6 THE DEPLOYMENT ZONE

The crux of the protocol is to define a region relative to ISS that a deployed/jettisoned payload can exist in the defined six (6) or eight (8) day window. This region is the “Deployment Zone (DZ)”. Theoretically, this is the only space that a deploy can occupy during the six (6) or eight (8) day window after deployment/jettison from the ISS within the assumptions of the analysis. This analysis was conducted with various payload sizes and masses to define the size of the envelope. If GPM is outside of this zone, then the deploy will not conjunct with GPM in six (6) or eight (8) days post-deploy. In the same vein, if it can be shown that the object(s) will not overtake GPM in terms of downtrack distance from ISS or GPM will not overtake the object(s) or if GPM stays entirely above or below the possible deploy trajectories for six (6) or eight (8) days, then there is no possibility for a conjunction between the object and GPM during this time of concern. Figure 7-2 shows the relative motion of a worst case analysis that defined the envelope for the Deployment Zone.

The bounding cases for a deploy are dependent on the physical characteristics of the deploy, the operational plan of the deploy, the deployer, the physical characteristics of the ISS, the operational plan of the ISS and atmosphere. The trajectory which will separate farthest and quickest from the ISS would have the maximum deploy speed, the deploy direction closest to exactly retrograde, the lowest ballistic number for the deploy, the highest ballistic number for ISS and the most dense atmosphere. Similarly, the trajectory which separates least and slowest lies on the opposite end of the spectrum for those same variables. The ballistic number is a relation that is dependent on the physical characteristics of an object. It is inversely related to the acceleration due to drag on an object, as shown below. Therefore, a higher ballistic number object would decay less than an object with a lower ballistic number.

$$\begin{aligned}
 \text{ballistic number, } BN &= \frac{m}{C_d A} \\
 \text{force due to drag, } F_D &= \frac{1}{2} \rho V^2 C_d A \\
 \text{acceleration due to drag, } a_D &= \frac{1}{2} \rho V^2 \frac{C_d A}{m} = \frac{1}{2} \rho V^2 \frac{1}{BN}
 \end{aligned}$$

Unless evidence is supplied to suggest otherwise, a C_d of 2.0 is assumed. The frontal area, A , is dependent on if the deploy has any attitude control, if there is evidence it will settle into a certain configuration or if a frontal area based on a random tumble, equal to a quarter of the object surface area, should be assumed. A random tumbling configuration is assumed to be the minimum ballistic number frontal area in the absence of attitude control or evidence to support a specific configuration.

To minimize repeated analysis, a set of generic tables and deploy profiles were created. Two tables were created, one for 6 days post deploy and one for 8 days post deploy. Each table shows the downtrack distance, radial distance, and phase angle

based on deploy velocity. Three generic deploy velocities were chosen as bounding conditions: 0.5 m/s, 1.0 m/s, and 1.7 m/s. By using generic velocities, the need for analysis per individual deployer is eliminated. Each row of the table is a different ballistic number, which also includes a “no-drag” case to show the minimum possible separation in all three metrics. In addition, each row of the table has a trend line associated with the downtrack and radial growth profile for the minimum and maximum separation cases. Table 1 is included as an example.

To make use of this generic analysis, first, the number of objects being deployed in the campaign is determined. The time of the window depends on the number of deployed/jettisoned payloads. Per the Jettison Policy (9.5 ISS Jettison Policy), 4 days are allotted for JSpOC tracking for 3 or fewer objects and 6 days for more than 3. The GPM process to be able to identify a risk and plan/execute a debris avoidance maneuver is 2 days. The window can be 6 or 8 days depending on the deploy/jettison plan. Therefore, two separate tables are required to provide the data for both 6 and 8 days post deployment. Second, of the planned jettisons or deploys, the object with the lowest ballistic number (BN) would define the deployment zone based on Table 1. The more conservative distance will be used; for example, if an object has a ballistic number of 26, the deployment zone distance will correspond to the ballistic number of 20 case. Finally, the deploy velocity of the object is needed. The increments chosen to be represented in this analysis were 0.5 m/s, 1.0 m/s, and 1.7 m/s. The value of .5 m/s and 1.0 m/s were chosen to represent the velocities of the various deployers on the ISS. The value of 1.7 m/s was based upon the maximum deploy velocity of the NanoRacks CubeSat Deployer. The choice of which deploy speed column to use depends on the maximum deploy speed of the deployer. If the deployer max speed is between values, the higher speed column is chosen. The ballistic number and deploy speed set the row and column in the table. If GPM is outside of the radial or downtrack distance listed for the entire time of concern then there is no concern for the deploy with respect to GPM. If not, the trend lines associated with the specific row can be used to determine if the deploy overtakes GPM or vice versa or if the deploy stays above or below GPM over the time of concern. An illustration of this is shown in Figure 7-1. The red and light blue lines represents the downtrack growth profiles for bounding cases for a particular deploy. The area between these lines represents the potential location of the deployed object; it is not safe if GPM falls within these lines. If GPM is outside of these lines, as shown, then the deployed object poses no risk to GPM for the given assumptions. Case-by-case analysis will be required for situations outside the assumptions stated.

	.5 m/s			1.0 m/s			1.7 m/s		
BN [kg/m^2]	Down- track Ahead [km]	Radial Distance [km]	Phase Angle ¹	Down- track Ahead [km]	Radial Distance [km]	Phase Angle	Down- track Ahead [km]	Radial Distance [km]	Phase Angle
10	3550	12	30.0°	4139	13	35.0°	4965	15	41.9°
20	1915	6	16.2°	2484	7	21.0°	3260	9	27.7°
30	1386	4	11.7°	1948	5	15.5°	2735	7	23.1°
40	1124	3	9.5°	1683	4	14.2°	2466	6	20.8°
60	864	2	7.3°	1420	3	12.0°	2198	5	18.6°
80	735	2	6.2°	1289	3	10.9°	2065	5	17.5°
100	657	1	5.5°	1211	3	10.2°	1985	4	16.8°
No Drag	547	1	4.6°	1095	3	9.3°	1861	4	15.7°

Table 1: 6-day Deployment Zone Table Example

¹ This is calculated at ISS altitude where ~118km is equivalent to about 1°.

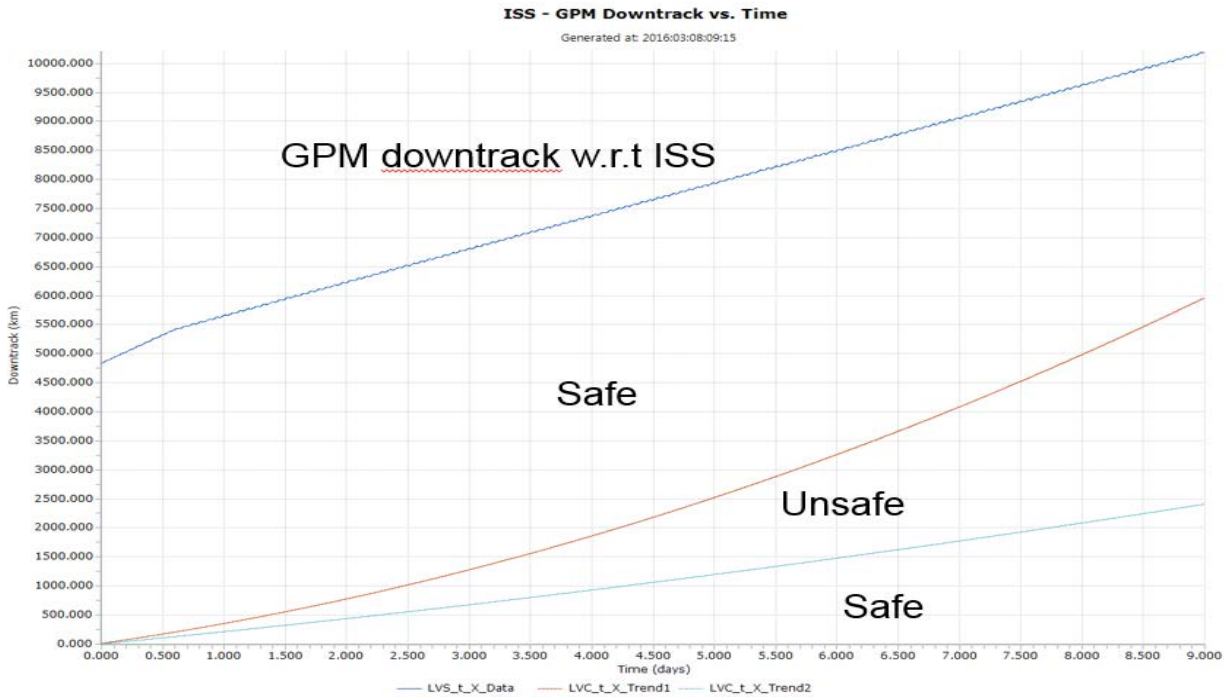


Figure 7-1: Deployment Zone w.r.t. Time Example

GPM and ISS agree that the Deployment Zone is defined as an along track distance that begins at the ISS relative position and extends some distance in front of ISS in the velocity direction. This distance is dependent on the jettison speed (deployer & CubeSat mass) and the CubeSat Ballistic Number (BN).

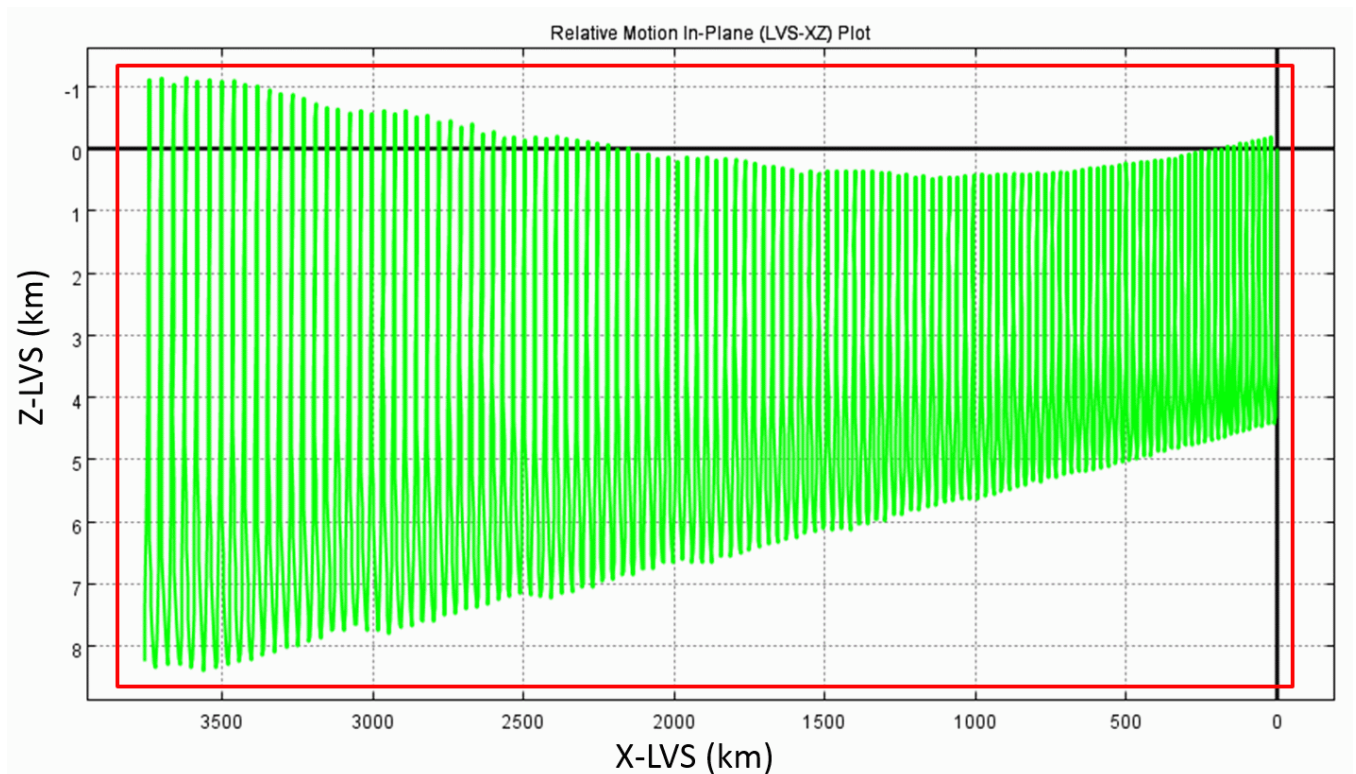


Figure 7-2: Deployment Zone Example

7 DATA SHARING

The following data sharing agreements are to ensure that the ISS and GPM teams are aware of the upcoming deployments and preventative actions of both missions can be completed.

- Agreement #15: ISS agrees to alert GPM for planned deployments and jettisons. Alerts shall include the deployment item(s) and the planned deployment date and time, the size, mass and expected deployment velocity expected at least a month in advance.²
- Agreement #16: ISS agrees to alert GPM 24 hours following successful deployments and jettisons³. Alerts shall include the deployment item name(s), the date and time of deployment and the JSpOC catalog ID.

In order to ensure that both ISS and GPM can calculate if GPM is (or will be) in the Deployment Zone, both missions need to share predicted ephemeris data. The ephemeris data will be used by both teams to calculate the distance between GPM and ISS. Figure 8-1 shows an example of the results of this calculation. However, this distance plot is not a pure down track measurement but also includes a component of cross-track since the inclination of ISS and GPM differ significantly.

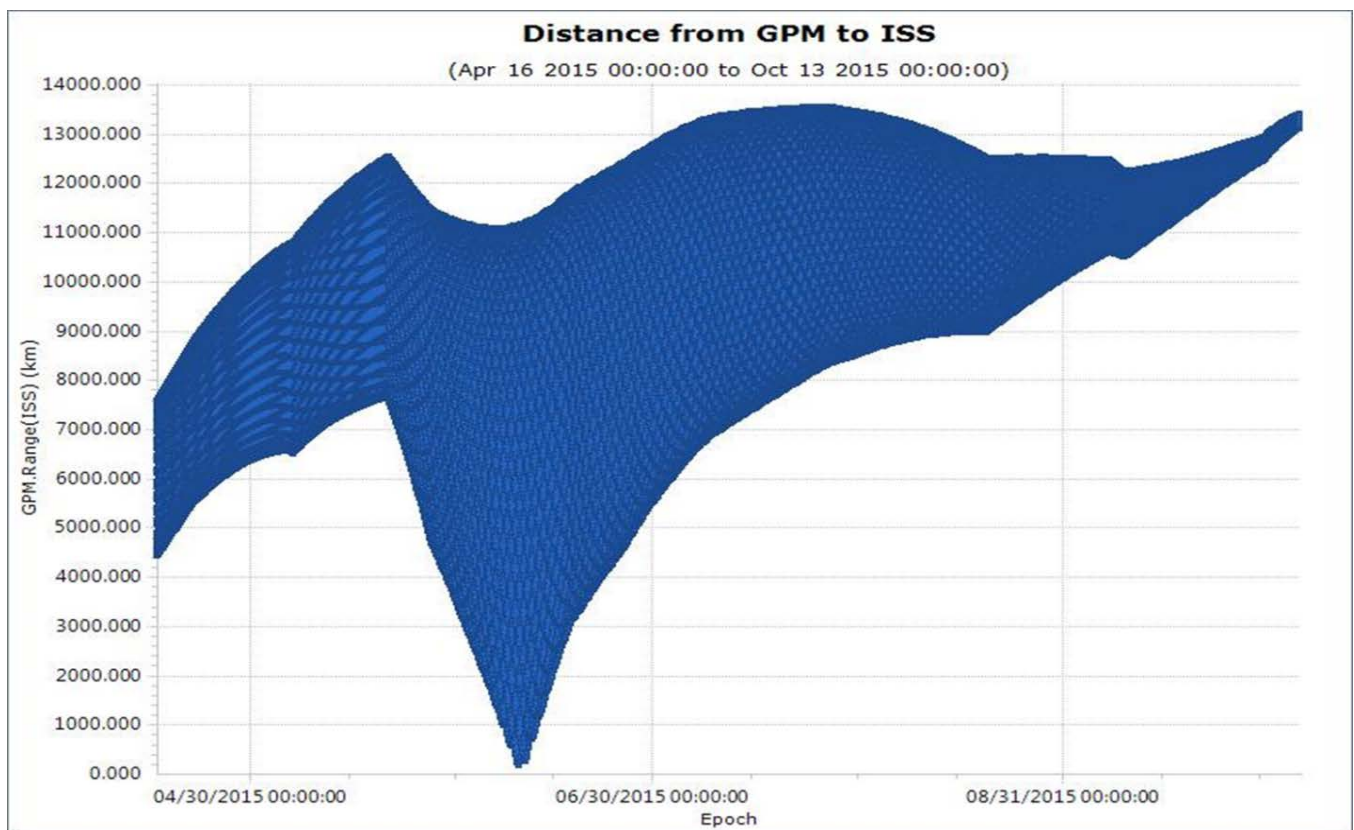


Figure 8-1: Example Distance Plot between GPM and ISS

Figure 8-3 shows an example that relates the distance to an along track “phase angle”, where positive phase angle is when GPM is in front of ISS, a negative phase angle is when GPM is behind ISS, and a phase angle of 180° represents GPM on the other side of the Earth relative to ISS. In this plot, ISS is along the $y=0^\circ$ phase angle and GPM flies along the blue line. This calculation is based entirely upon the down-track component, and is more useful in depicting the Deployment Zone. In this example, the Deployment Zone is up to 34.5°⁴.

² ISS/TOPO will keep GPM informed of long term planned deploys on a best effort basis

³ The JSpOC Catalog ID will usually lag the deployment/jettison alert by a day or two.

⁴ This is calculated at ISS altitude where ~118km is equivalent to about 1°.

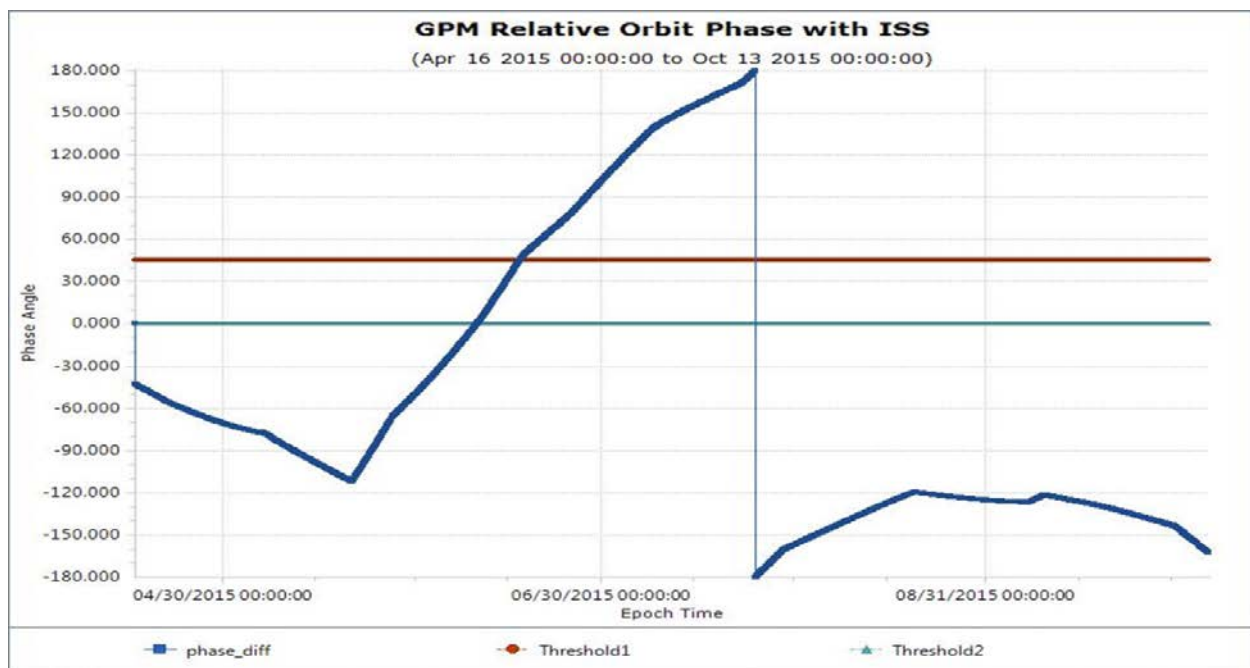


Figure 8-2: Example Phase Angle Plot

Predicted ephemerides from ISS and GPM are required to generate this plot. In addition, it is incumbent upon both to use their respective trajectory planning software to generate to assure themselves the relative phasing of the missions. The next two agreements allow both to independently create it, allowing for comparison and validation of process.

- Agreement #17: ISS/TOPO agrees to provide a weekly⁵ predicted ephemeris (8-week span) to the GPM FOT for purposes of predicting GPM/ISS separation distance and Drag Make-Up Maneuver (DMUM) planning and monthly 6-month long term predicted ephemeris.
- Agreement #18: GPM agrees to provide ISS/TOPO a weekly predicted ephemeris (30-day span) for purposes of predicting GPM/ISS separation distances.⁶

8 SAFE DEPLOYMENTS

Following these preventative actions will not assure that GPM is not in the Deployment Zone, but will help to minimize the impact to ISS deploys/jettisons by attempting to remain outside the Deployment Zone to the greatest extent.

- Agreement #19: ISS/TOPO and GPM agree that deployments and jettisons are safe deployments if GPM will be flying outside of the Deployment Zone based on deployed/jettison objects Ballistic Number as defined by generic or cased specific analysis at the time of deployment.⁷

9 NON-SAFE DEPLOYMENTS

While this analysis can cover the majority of the deployment/jettison cases and definitively declare safe deployments with regard to GPM, it cannot categorically declare that deployments/jettisons made while GPM is in the Deployment Zone are unsafe. Rather, this analysis can be used to single out deployments/jettisons that will need further analysis and/or will only be made with inherent risk to collision with GPM. For these cases, ISS/TOPO will lead the analysis to assure GPM that the risk is acceptable.

⁵ This data routinely is produced weekly, but at times, based on operational considerations, may be produced less frequently.

⁶ For special events and deployments, ad-hoc requests may be requested and will be provided to support the safe deployment

⁷ Depending on the time away from deployment, and the proximity of GPM to the Deployment Zone, this may be calculated several times to ensure results are accurate.

- Agreement #20: When there is a future projected violation of the Deployment Zone by GPM during an anticipated deployment/jettison, GPM agrees to alter their DMUM schedule, to the greatest operational extent⁸ while maintaining all GPM operational requirements related to orbit, in order to avoid or minimize the duration that GPM is resident in the Deployment Zone.
- Agreement #21: GPM agrees to alert ISS as to the changes made to the DMUM plan that attempts to minimize the time GPM is expected to reside in the Deployment Zone.
- Agreement #22: ISS/TOPO agree that in the case of deployment/jettison events that do not meet all criteria in Agreement #19:, the ISS/TOPO group will conduct further nodal analysis of the specific CubeSat/item to detail that the deployment will not pose a collision risk to GPM. The next level nodal analysis will evaluate the relative geometry at the common nodes which represents the only place a collision could actually occur. The relative geometry will be evaluated accounting for GPM and the specific Cubesat uncertainties. The analysis will be shared with GPM for concurrence.
- Agreement #23: ISS/TOPO agree that for planned deployments that cannot meet Agreement #19: or Agreement #22:, the deployment will be reported to ISS and GPM programs as a collision risk and the deployment/jettison will not occur until the risk can be discussed. TOPO, GPM Flight Dynamics and CARA will support the discussions.


10 IMPLEMENTATION

In practice, the implementation has flowed very successfully, as both ISS and GPM teams are committed to keeping each vehicle safe.


For example, in January of 2016, ISS deployed the cubesat LoneStar from the Cyclops deployer. Prior to the deployment, on November 5TH, 2015, the ISS TOPO team shared the plans with GPM in a presentation that detailed the vehicle and the expected operations.

LONESTAR

- LONESTAR
 - Objective: prox ops experiments
 - Deployed from Cyclops
 - BN ~90 kg/m²
 - Active attitude control
 - AggieSat4 parent
 - BN ~84 kg/m²
 - Bevo-2 child
 - Propulsive capabilities
 - Deploy prohibited well beyond tracking time frame due to ISS recontact concerns
 - Manifested on OA-4



LONESTAR w/ integrated Bevo-2 Satellite



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10

Figure 11-1: TOPO Notification and description slide 11/05/2015

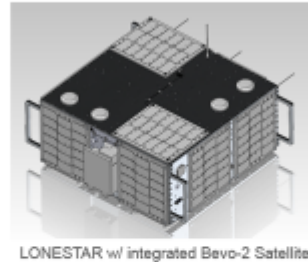
This was followed up on January 7TH, 2016 with additional information when the deployment was scheduled.

⁸ GPM must maintain the geodetic height to ensure good science data for the mission. Additional operational constraints in the timing of the DMUM may further limit changes.

LONESTAR

- LONESTAR

- Objective: prox ops experiments
- Deployed from Cyclops
- BN $\sim 90 \text{ kg/m}^2$
- Active attitude control
- AggieSat4 parent
 - BN $\sim 84 \text{ kg/m}^2$
- Bevo-2 child
 - Propulsive capabilities
 - Deploy prohibited well beyond tracking time frame due to ISS recontact concerns
- Delivered on OA-4
- **Scheduled for week of 1/25**



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7

With the information provided, the ISS/TOPO group and GPM agreed to use the 6-day deployment table, and determined the Deployment Zone for this deploy to be 735km (6.2°). This was arrived by using the closest BN row not greater than the CubeSat's BN (80), and column of the table not greater than the relative deploy speed of Cyclops of 0.18 m/s (0.5 m/s). Table 5 shows the process.

BN [kg/m ²]	.5 m/s			1.0 m/s			1.7 m/s		
	Down-track Ahead [km]	Radial Distance [km]	Phase Angle ⁹	Down-track Ahead [km]	Radial Distance [km]	Phase Angle	Down-track Ahead [km]	Radial Distance [km]	Phase Angle
10	3550	12	30.0°	4139	13	35.0°	4965	15	41.9°
20	1915	6	16.2°	2484	7	21.0°	3280	9	27.7°
30	1386	4	11.7°	1948	5	16.5°	2735	7	23.1°
40	1124	3	9.5°	1683	4	14.2°	2466	6	20.8°
60	864	2	7.3°	1420	3	12.0°	2198	5	18.6°
80	735	2	6.2°	1289	3	10.9°	2065	5	17.5°
100	657	1	5.5°	1211	3	10.2°	1985	4	16.8°
No Drag	547	1	4.6°	1095	3	9.3°	1861	4	15.7°

Figure 11-2: 6-Day Deployment Zone Tables

Based upon the agreed Deployment Zone, ISS/TOPO shared the In-Plane Relative Motion plot between GPM & ISS, Figure 11-3, on January 20TH, 2016. In the plot, ISS is at the origin moving to the left, and GPM follows the blue line starting from the green dot to the red dot. The Deployment Zone is depicted in the red box.

⁹ This is calculated at ISS altitude where $\sim 118\text{km}$ is equivalent to about 1° .

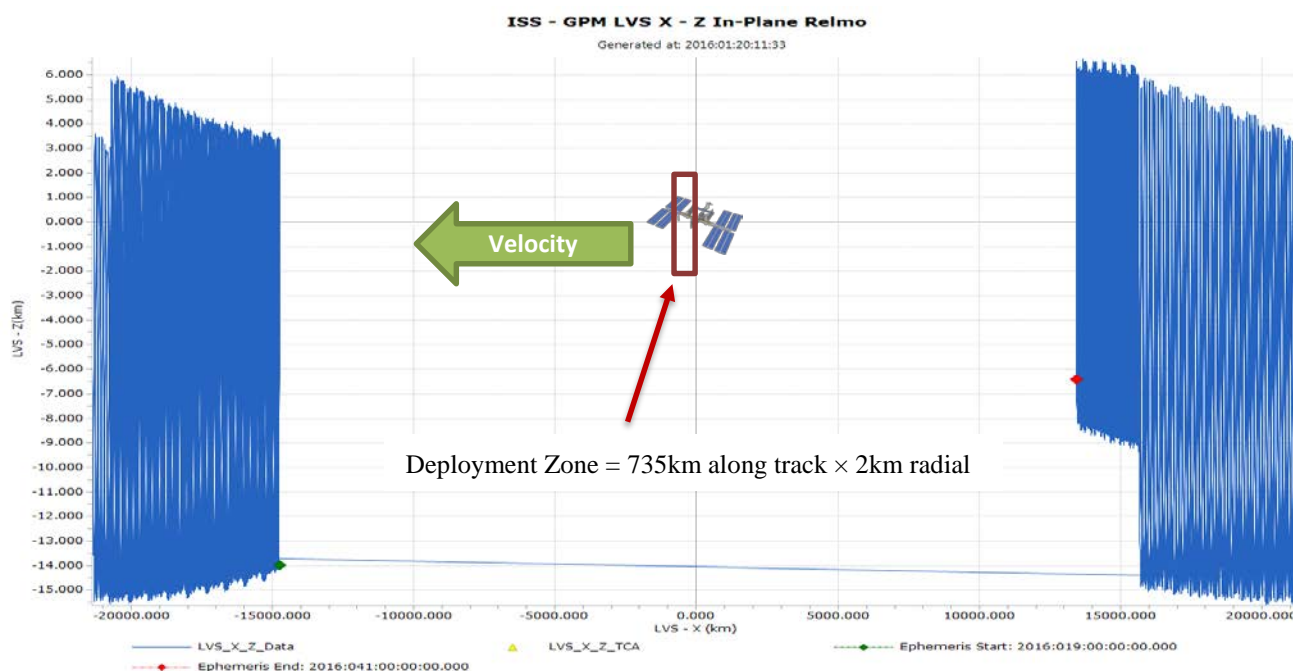


Figure 11-3: ISS/TOPO Relative Motion Plot

In return, GPM operations generated a phase plot, Figure 11-4, providing independent evidence of GPM not being within the Deployment Zone for the 4-days. This was shared with the ISS/TOPO group. In addition, GPM agreed that there were no violations of the Deployment Zone and had no issues with the planned deployment.

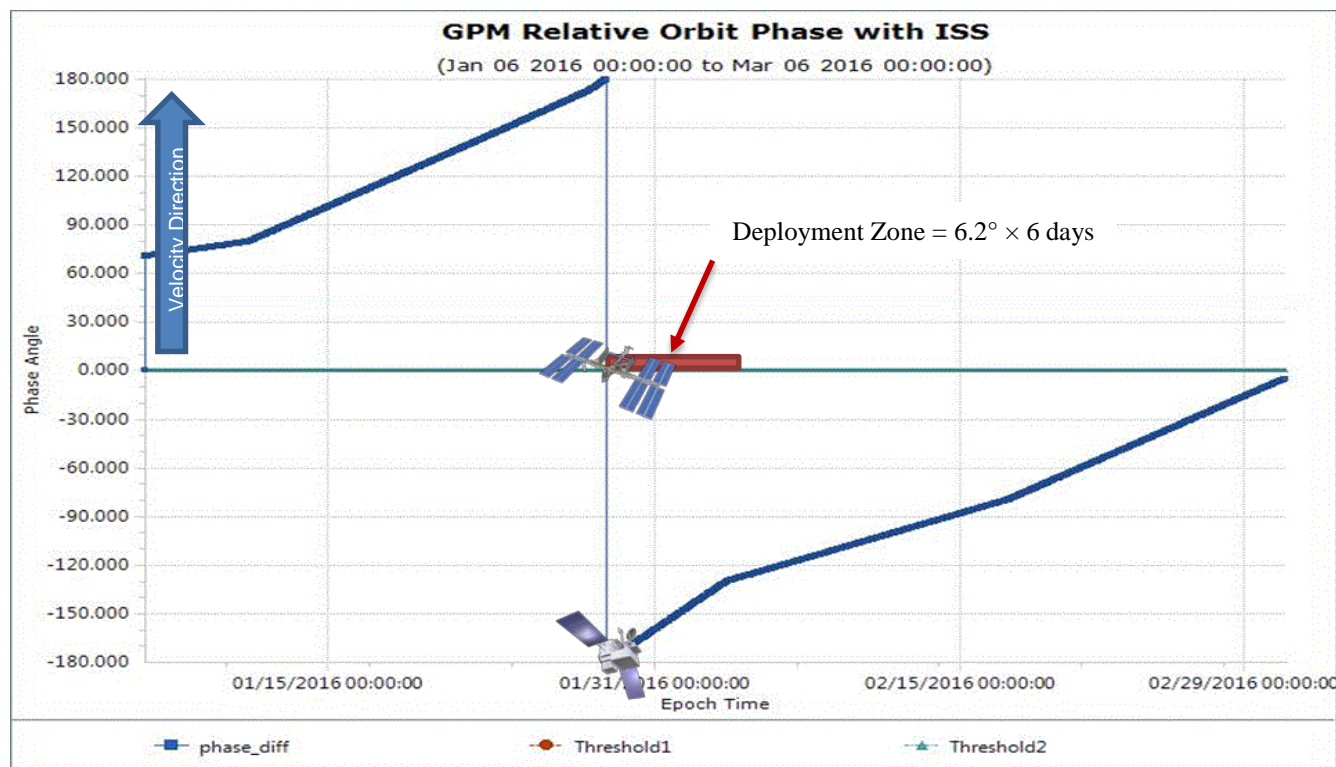


Figure 11-4: Relative Phase Plot from GPM

On January 29TH, at 15:55:48GMT, LONESTAR was successfully deployed from the ISS without incident. GPM was notified within hours of the deploy. JSpOC tracked and catalogued LoneStar (as object 41313, “AggieSat-4”) on January 30TH @ 00:21:59, well within the 6-day window.

11 SUMMARY

In conclusion, the ISS and GPM teams have developed and implemented a quick and effective strategy to allow safe cubesat deployments from the ISS while in the same altitude regime as another valuable NASA asset.

The strategy relies upon well thought out communications and knowledge of the other mission gained through the sharing of information between the missions including predicted trajectories, maneuver plans and planned deployments. Both missions mutual understanding of the risk of close approaches provides common ground for development and continued application of the agreement. The first order solution efficiently identifies which candidates pose little risk and which require further investigation. Thus, low risk cases have a negligible workload impact and high risk cases are not missed.

In the early stages of use, this process has yielded very successful results and further improvements are expected to be made over time.